

# Glueballs and vector mesons at NICA

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**Abstract.** Two interconnected fields of interest are suggested for NICA. Firstly, existence of glueballs is predicted by the theory of strong interaction but – even after decades of research – glueball identification in the physical spectrum is still unclear. NICA can help to ascertain experimental glueball candidates via  $J/\Psi$  decays whose yield is expected to be large. Importance of glueballs is not limited to vacuum: since they couple to other meson states, glueballs can also be expected to influence signatures of chiral-symmetry restoration in the high-energy phase of strong dynamics. Mass shifting or in-medium broadening of vector and axial-vector mesons may occur there but the extent of such phenomena is still uncertain. Additionally, glueball properties could also be modified in medium. Exploration of these issues is the second suggested field of interest that can be pursued at NICA.

**PACS.** 12.39.Mk Glueball and nonstandard multi-quark/gluon states – 14.40.Be Light mesons

## 1 Introduction

Quantum Chromodynamics (QCD), the established theory of the strong interaction, is per construction of non-Abelian nature. As a consequence, gauge bosons of QCD – the gluons – are self-interacting. Since the strong coupling is large at sufficiently small energies [1,2], the expectation is that the non-perturbative region of strong dynamics enables gluons to build more complex objects denoted as glueballs [3,4,5,6,7,8,9,10]. Theoretical studies have shown lively interest in glueballs using various methods to approach the non-perturbative regime of QCD:

- Ab-initio numerical calculations in lattice QCD have resulted in predictions of glueball spectra in quenched as well as unquenched approximations [11,12,13,14,15,16,17,18,19,20,21].
- The AdS/CFT correspondence has yielded results both on glueball spectra [22,23,24,25,26] as well as decays of glueballs [27,28,29,30]; an exemplary approach in this direction is briefly outlined in Sect. 2.
- Effective approaches to QCD have upon implementation of relevant symmetries of strong dynamics considered not only glueball decays but also various mixing mechanisms between glueball and non-glueball states obtaining a satisfactory overall agreement with experimental data [31,32,33,34,35,36,37,38]; see also Refs. [39,40,41].

There are several reasons for interest in glueballs:

- Glueballs are unique since their mass is, at the leading order, generated solely via self-interaction of gluons (pure gluodynamics). Although at the level of full QCD

current quark masses can contribute, their effects are currently unclear. This is particularly the case in lattice QCD where the inclusion of dynamical fermions leads to the emergence of states additional to those present in pure gluodynamics with consequences that, *e.g.*, (i) states experience overlaps and (ii) the scalar glueball is no longer the lowest state of the spectrum. Then the identification of states is more complicated – and conclusions from lattice QCD in the scalar channel somewhat conflicting: Refs. [16,19,20] do not observe large unquenching effects in simulations relying on staggered fermions while a different opinion (in line with the expectation of Ref. [15]) is advocated by simulations with clover fermions [18].

Leading-order mass generation of glueballs is in contrast to other strongly interacting particles (*i.e.*, hadrons) whose masses are predominantly generated by quark dynamics and thus susceptible to, albeit very small, contribution of the Brout-Englert-Higgs mechanism (see examples for pions [42]; kaons [43];  $\omega$ - $\rho$  splitting [43,44]; nucleons [45]).

Therefore glueballs represent a very important tool to explore strong dynamics.

- The spin of glueballs is integer since gluons are vector particles. Consequently the spectrum of mesons (*i.e.*, hadrons of integer spin) would be incomplete if glueballs were omitted from experimental searches.

In Sect. 3, some of the issues on the experimental side of the glueball search are exemplified, together with suggestions for NICA in this regard.

Already in vacuum, glueballs couple to non-glueball states (possessing  $\bar{q}q$ ,  $\bar{q}\bar{q}qq$  and other valence degrees of freedom).

The expectation is that a coupling of modified strength will remain at non-zero temperatures and densities. In that case, glueballs will influence  $\bar{q}q$  states and the underlying phenomena of their in-medium behaviour, such as the chiral-symmetry restoration. It is, however, unclear what this behaviour exactly entails since vector and axial-vector mesons may shift in mass or become broader in medium but clear experimental evidence for this is still outstanding. These issues together with further suggestions for NICA are discussed in Sect. 4. Conclusions are presented in Sect. 5.

## 2 Hallmarks of a glueball: an example

A glueball state can be distinguished from other hadrons by for example (i) strong suppression in two-photon decay channels [46] and prominent presence in radiative decays [21]; (ii) decay patterns. Various approaches to glueball dynamics (mentioned in the previous section) have been applied in studies of glueball decays; in the following, a recent approach based on the AdS/CFT correspondence is briefly discussed and its results for glueball identification are presented.

The approach is based on the conjectured duality between weakly coupled string theory (*i.e.*, supergravity) in an anti-de Sitter (AdS) space and a strongly coupled conformal field theory (CFT) in one dimension less [47]. The field theory possesses symmetries absent from QCD (supersymmetry in addition to conformality); these are removed by suitable compactifications in the full supergravity space [48] and the emerging  $U(N_c)$  gauge theory (with  $N_c \rightarrow \infty$ ) may be used to explore the Yang-Mills sector of QCD. Then (holographic) glueballs are obtained as graviton polarisations in the supergravity background. It was demonstrated in Ref. [22] that such an approach leads to a glueball spectrum that is remarkably similar to the one obtained in lattice-QCD simulations.

Studying glueball decays into  $\bar{q}q$  states requires introduction of quark degrees of freedom. A method to include chiral quarks – the so-called Witten-Sakai-Sugimoto (WSS) Model – was proposed in Refs. [49, 50] by introducing  $N_f$  (number of flavours) probe D8- and anti-D8-branes in the supergravity space that extend along all dimensions in the space except for a (Kaluza-Klein) circle. D-branes introduce a  $U(N_f) \times U(N_f)$  symmetry in the theory; since D8- and anti-D8-branes merge at a certain point in the bulk space, the original  $U(N_f) \times U(N_f)$  symmetry is reduced to its diagonal subgroup. This is interpreted as a geometric realisation of chiral-symmetry breaking.

It was demonstrated already in Refs. [49, 50] that the WSS Model can describe phenomenology of  $\bar{q}q$  states at least in a semiquantitatively correct way. Decays of dilaton glueballs were in turn explored in Refs. [28, 29] where predictions for decays of the scalar and tensor glueballs in the  $2\pi$ ,  $4\pi$ ,  $6\pi$ ,  $2K$  and  $2\eta$  channels have been made, as presented in Tables 1 and 2.

However, irrespective of the lively theoretical interest in glueballs, the identification of these states in the physical spectrum is still outstanding.

## 3 Experimental ambiguities relevant for glueballs: an example, and a suggestion for NICA

Reasons for problems in experimental identification of glueballs are at least twofold:

- Glueballs are expected to emerge starting at energies between approximately 1.5 GeV and 1.8 GeV where the ground state, a scalar [51], is predicted in numerical simulations of the spectrum [11]. Historically there has been a scarcity of precise experimental data exactly in the energy region where glueballs are expected to emerge [52]. Although there has been a notable change in data availability [53, 54, 55], the amount of progress is still not sufficient for an unambiguous identification of these states.
- Glueball with a given set of quantum numbers will inevitably mix/interfere with non-glueball states (possessing  $\bar{q}q$ ,  $\bar{q}q\bar{q}q$  and other valence degrees of freedom) that have the same quantum numbers. The effects of

**Table 1.** Comparison of holographic scalar-glueball decays (the outer right column) obtained in Ref. [28] with experimental data for the two prime candidates for the scalar glueball, the resonances  $f_0(1500)$  and  $f_0(1710)$ . The 't Hooft coupling (that is the only free quantity in the WSS Model, except for the Kaluza-Klein mass which sets the Model scale) was determined in two ways, by implementing the experimental value of the pion decay constant or the lattice-QCD value of the string tension. This allows for theoretical uncertainties to be estimated and hence holographic results are presented in intervals. All experimental data are from PDG [52] except for those marked by a star that are from Ref. [63] where the  $f_0(1710)$  decay channels were calculated assuming a negligible coupling of that resonance to  $4\pi$ . All masses are in MeV. The  $f_0(1710)$  resonance is preferred to have a significant overlap with the scalar glueball but a conclusive statement in this regard is hampered by experimental uncertainties discussed in Sect. 3.

Decay	$M_{\text{exp.}}$	$\Gamma/M$ (exp.)	$\Gamma/M$ (holography)
$f_0(1500)$ (total)	1505	0.072(5)	0.027...0.037
$f_0(1500) \rightarrow 4\pi$	1505	0.036(3)	0.003...0.005
$f_0(1500) \rightarrow 2\pi$	1505	0.025(2)	0.009...0.012
$f_0(1500) \rightarrow 2K$	1505	0.006(1)	0.012...0.016
$f_0(1500) \rightarrow 2\eta$	1505	0.004(1)	0.003...0.004
$f_0(1710)$ (total)	1723	0.078(4)	0.059...0.076
$f_0(1710) \rightarrow 2K$	1723	0.047(17)*	0.012...0.016
$f_0(1710) \rightarrow 2\eta$	1723	0.022(11)*	0.003...0.004
$f_0(1710) \rightarrow 2\pi$	1723	0.009(2)*	0.009...0.012
$f_0(1710) \rightarrow 4\pi$	1723	?	0.024...0.030
$f_0(1710) \rightarrow 2\omega \rightarrow 6\pi$	1723	seen	0.011...0.014

**Table 2.** Decays of the holographic tensor glueball predicted by the WSS Model for two different masses,  $M_T = 2000$  MeV and  $M_T = 2400$  MeV [28]. The former mass is chosen to approximately correspond to that of the  $f_2(1950)$  resonance, a possible candidate for the tensor glueball due to its mostly flavour-blind decay modes; for this state,  $\Gamma/M = 0.24(1)$  where  $\Gamma$  is the total decay width [52]. The value  $M_T = 2400$  MeV is chosen exemplary as an element of the interval for the tensor-glueball mass predicted by lattice QCD [11, 14, 15, 17, 20]. Just as for results presented in Table 1, the 't Hooft coupling was determined in two ways: by implementing the experimental value of the pion decay constant or the lattice-QCD value of the string tension. Holographic results are thus presented in intervals in order to estimate theoretical uncertainties.

Decay	$M_T$ (MeV)	$\Gamma/M_T$ (holography)
$T \rightarrow 2\rho \rightarrow 4\pi$	2000	0.135...0.178
$T \rightarrow K^*K^* \rightarrow 2(K\pi)$	2000	0.119...0.177
$T \rightarrow 2\omega \rightarrow 6\pi$	2000	0.045...0.059
$T \rightarrow 2\pi$	2000	0.014...0.018
$T \rightarrow 2K$	2000	0.010...0.013
$T \rightarrow 2\eta$	2000	0.0018...0.0024
$T$ (total)	2000	$\approx 0.32...0.45$
$T \rightarrow K^*K^* \rightarrow 2(K\pi)$	2400	0.173...0.250
$T \rightarrow 2\rho \rightarrow 4\pi$	2400	0.159...0.211
$T \rightarrow 2\omega \rightarrow 6\pi$	2400	0.053...0.070
$T \rightarrow 2\phi$	2400	0.032...0.051
$T \rightarrow 2\pi$	2400	0.014...0.019
$T \rightarrow 2K$	2400	0.012...0.016
$T \rightarrow 2\eta$	2400	0.0025...0.0034
$T$ (total)	2400	$\approx 0.45...0.62$

such interference in experimental data render the identification of resonances in general, and thus glueballs in particular, highly non-trivial [56].

Existing issues in experimental glueball searches can be illustrated by the following example relevant for the scalar glueball. This state possesses quantum numbers  $IJ^{PC} = 00^{++}$  where  $I$ ,  $J$ ,  $P$  and  $C$  respectively denote the isospin, total spin, parity and charge conjugation. Particle Data Group (PDG) cites the existence of five  $IJ^{PC} = 00^{++}$  resonances in the energy region up to  $\sim 1.8$  GeV:  $f_0(500)$ ,  $f_0(980)$ ,  $f_0(1370)$ ,  $f_0(1500)$  and  $f_0(1710)$ . They are known as scalar isoscalar resonances [52]; for a brief review, see Refs. [57, 58]. Claims have been made [59, 60, 61, 62] that a sixth such state exists, namely  $f_0(1790)$  – a state very close to  $f_0(1710)$  but with a different decay behaviour:  $f_0(1790)$  decays predominantly into pions whereas  $f_0(1710)$  decays predominantly into kaons.

There are four basic production mechanisms for  $f_0(1710)$  and  $f_0(1790)$  via  $J/\psi$  decays:

- (i)  $J/\psi \rightarrow \phi K^+ K^-$ ,
- (ii)  $J/\psi \rightarrow \phi \pi^+ \pi^-$ ,
- (iii)  $J/\psi \rightarrow \omega K^+ K^-$ ,
- (iv)  $J/\psi \rightarrow \omega \pi^+ \pi^-$ .

Reactions (i) and (iii) allow for reconstruction of  $f_0(1710)$  – see Ref. [64] – whereas  $f_0(1790)$  is reconstructed from reactions (ii) and (iv). Importantly, assuming  $f_0(1710)$  and  $f_0(1790)$  to be the same resonance leads to a contradiction: such a resonance would have to possess a pion-to-kaon-decay ratio of  $1.82 \pm 0.33$  according to reactions (i) and (ii) and a pion-to-kaon-decay ratio  $< 0.11$  according to reactions (iii) and (iv) [61, 62]. Decay ratios must be independent of the production mechanism for a single resonance. The assumption that  $f_0(1710)$  and  $f_0(1790)$  represent a single resonance clearly leads to a contradiction in the value of the mentioned decay ratio; consequently, the employed data – obtained by the BES Collaboration – prefer  $f_0(1790)$  as a resonance distinct from  $f_0(1710)$ . Nonetheless, additional inspection of this claim is by all means needed in further experiments.

If the existence of the  $f_0(1790)$  resonance is confirmed, it will most certainly have implications for glueball search since its mass is within the interval in which the scalar glueball is expected to appear according to lattice QCD.

NICA [65] program focused on the Spin Physics Detector (SPD) [66, 67] appears to be relevant for the issue of  $f_0(1790)$  but could also discover further resonances. If the Monte Carlo simulations of  $J/\psi$  production rates at SPD prove correct, then the yearly yield of these resonances should amount to  $\sim 10^7$  events [66, 67]. It would thus be of the same magnitude as that of BES II [61, 62], where the best available evidence for the existence of  $f_0(1790)$  has been presented – and then a careful reconstruction of resonances in  $2\pi$  final states emerging from  $J/\psi$  decays could clarify whether  $f_0(1790)$  exists. New resonances even higher in energy may also be discovered or those for which there is already indication –  $f_0(2020)$ ,  $f_0(2100)$ ,  $f_0(2200)$ ,  $f_0(2330)$  [52] – could be confirmed.

Comparison of SPD with other running or planned programs is in order. Given the above data on  $f_0(1790)$ , two sorts of production mechanisms are particularly relevant: (i)  $e^+e^-$  (as at BES) and (ii)  $pp$  (since planned at SPD).

Firstly,  $e^+e^-$  collisions at the VEPP-4M Collider have produced  $\sim 7$  million  $J/\psi$  events, as reported by the KEDR Collaboration [68]. This could in principle enable the reconstruction of  $f_0(1790)$  but an even larger  $J/\psi$  yield is expected at SPD.

Additionally, CMD-3 and SND Collaborations at VEPP-2000 can use  $e^+e^-$  collisions for scans of the energy region from hadron-production threshold up to 2 GeV but their focus is currently on vector mesons only [69], and SPD could fill this gap.

Note further that, although the primary focus of Belle-II [70] is on precision measurements beyond the Standard Model, discoveries in non-perturbative QCD can be expected also from that source given the large expected luminosity (larger than at SPD). Belle-II will rely on reconstruction of resonances from  $\Upsilon(4S)$  rather than  $J/\psi$  decays; particles below 2 GeV may be nonetheless recon-

structable but, given the large difference in mass and the well-known issues of overlapping scalar states, great care will have to be given to proper data analysis. Lower statistics should be sufficient for SPD to reach the same goal since the  $J/\Psi$  production is expected to be abundant.

Proton-proton collisions are nowadays most prominent at the LHC. It is clear that the LHCb [55], TOTEM [71] and ALICE [72] Collaborations can draw on huge cross-sections obtained at very large energies. Nonetheless, a comparative advantage of the SPD program is the use of polarised proton and deuteron beams that were of enormous importance for meson discoveries in the past [56].

Historically, proton-proton collisions have always represented a method of meson research with a large discovery potential even at moderate beam energies [63] that has proven complementary to antiproton-proton [73] and pion-nucleon [74] collisions or to photoproduction [75, 76].

My suggestion is thus that NICA Collaboration measure at SPD the number of events as a function of centre-of-mass energy for  $2\pi$ ,  $2K$  and  $4\pi$  final states at energies above  $\sim 1.5$  GeV and carefully analyse the data for new resonances. Further final states can be analysed as the data become available. Glueball production may be copious in any of these channels, with results presented in Tables 1 and 2 suggesting a very prominent  $4\pi$  coupling both for scalar and tensor glueballs. The potential for the discovery of new resonances thus appears to be large, with consequences even for non-glueball states.

## 4 Vector mesons and NICA

There are four established resonances in the  $J^{PC} = 1^{--}$  (*i.e.*, vector) meson channel in the energy region up to approximately 1 GeV:  $\rho(770)$ ,  $\omega(782)$ ,  $K^*(892)$  and  $\phi(1020)$  [52]. In the  $J^{PC} = 1^{++}$  (*i.e.*, axial-vector) channel, the established resonances up to 1.5 GeV are  $a_1(1260)$ ,  $f_1(1285)$ ,  $K_1(1270)$ ,  $K_1(1400)$  and  $f_1(1420)$  with the  $K_1$  states possibly having noticeable admixture from the  $J^{PC} = 1^{+-}$  (pseudovector) channel [77]. Phenomenology of all of these resonances has been extensively studied in vacuum – see Refs. [78, 79] and refs. therein; chiral partners among these resonances can offer insight into important phenomena of high-energy QCD [80].

Current experimental ambiguities regarding mesons in medium can be illustrated by the following example: from the side of theory, general expectation is that the (axial-)vector masses will follow one of the following two scenarios:

- The mass decreases to zero as the chiral condensate vanishes (*i.e.*, the chiral symmetry of QCD becomes restored) – the “Brown-Rho scenario” [81].
- The mass remains essentially constant or decreases marginally as the chiral condensate vanishes – the so-called “constant-rho scenario” [80].

The constant-rho scenario is based on an observation, *e.g.*, from Linear Sigma Model with vector and axial-vector mesons that the  $\rho$  meson – although consistent with a  $\bar{q}q$  state [82] – actually has two contributions to its mass, one from the chiral and another from the gluon condensate; an overall meson study [37, 78, 79] then suggests that  $m_\rho$  is dominated by the gluon condensate rather than by the chiral one.<sup>1</sup>

Two questions are crucial: (*i*) the behaviour of the gluon condensate in medium; (*ii*) the behaviour of vector mesons in medium.

General conclusion from a range of approaches is that the gluon condensate is virtually unchanged below a critical temperature  $T_c$  whose value in lattice QCD is strongly dependent on whether pure gluodynamics is considered or, in addition, effects of massive quarks. For pure Yang-Mills QCD, there is a sharp drop of the gluon condensate at  $T_c \simeq 260$  MeV; however, if light quarks are present then the condensate exhibits a more gradual decrease between temperatures of  $\simeq 130$  MeV and  $\simeq 190$  MeV [83, 84, 85, 86]. Effective models of QCD have found the gluon condensate to remain stable up to  $T \simeq 200$  MeV [87, 88, 89]; see also Refs. [90, 91]. A similar result has been obtained from finite- $T$  renormalisation group equations [92].

Measurements of in-medium vector mesons have so far obtained conflicting results on the issue of mass shift but also on the related question of whether these resonances experience an in-medium broadening [93, 94, 95, 96, 97, 98, 99].

High-energy limit of QCD is dominated by a gluon-rich environment [100, 101, 102]. It is therefore quite possible that glueballs influence phenomena emerging in this phase of QCD, particularly scalar and tensor ones [103]. Lattice simulations in pure Yang-Mills QCD have found the scalar state to exhibit a mass decrease starting at  $T \geq 200$  MeV with a mass drop of approximately 300 MeV and a thermal decay width of  $\sim 300$  MeV at  $T = T_c$  [104]. The tensor mass is claimed to decrease only slightly below  $\sim 200$  MeV but, once  $T_c$  is reached, the mass drops by approximately 500 MeV and a thermal width of  $\simeq 400$  MeV is obtained. Similar results were obtained in lattice simulations presented in Ref. [105].

Additionally, T-matrix formalism of Ref. [106] finds the scalar glueball to start dissolving at  $T \sim (1.3 - 1.5)T_c$  while the dissolution onset for the tensor is at  $T \sim 1.15T_c$ . As the temperature increases, the scalar glueball becomes massless at  $T \sim 900$  MeV according to Ref. [107]; see also Refs. [108, 109].

Hence there are many theoretical predictions, and new

<sup>1</sup> It has to be noted here that the mentioned expectation is based on experimental data in vacuum that suffer from uncertainties discussed in Sect. 3. For this reason, improved measurements in vacuum physics would enable more precise theoretical predictions of in-medium meson properties.

experimental measurements are needed.

Two of the planned experiments at NICA appear to be relevant here: (i) MultiPurpose Detector (MPD) program intended to study hot and dense baryonic matter in heavy-ion collisions at a centre-of-mass energy up to 11 GeV [110, 111] and (ii) Baryonic Matter at Nuclotron (BM@N), focused on production of strange matter in heavy-ion collisions at beam energies between 2 AGeV and 6 AGeV [112, 113]. My suggestion is that NICA Collaboration perform a careful study of in-medium spectral functions for vector and axial-vector mesons listed at the beginning of this section – in this way information can be obtained on the mass shifts, decay properties and other phenomena that can improve theoretical studies of chiral-symmetry restoration.

A range of measurements has already been performed at RHIC [114] and LHC [115] exploring high temperatures and low baryon densities and at HADES [116] exploring lower temperatures and moderate densities. The main interest of NICA/MPD and BM@N is in the region of QCD phase diagram intermediate to the mentioned two, building on the results obtained at SPS [117]. Hence future measurements at NICA appear to open a unique possibility to study in particular (axial-)vector mesons at high densities and moderate temperatures. The Collaboration also estimates that collider experiments at MPD will have a nearly constant acceptance and occupancy, unlike the future FAIR/CBM experiment [118] that will rely on a fixed target. Exploration of (axial-)vectors under these conditions is obviously highly desirable.

As an example, the degeneration of the chiral partners  $\rho$  and  $a_1$  can be used as an order parameter for the chiral transition (see Refs. [80, 119, 120, 121] and refs. therein). Then there are three possible scenarios for the mass shifts of  $\rho$  and  $a_1$  in medium: (i) both masses decrease and become degenerate; (ii) both masses increase and become degenerate; (iii)  $m_\rho$  increases and  $m_{a_1}$  decreases leading to the degeneration of the two masses. Currently it is unclear which of these options is realised in strong dynamics and MPD/BM@N data could provide valuable information in this direction.

Note, however, that the physical  $\rho$  meson has also been suggested to represent a superposition of states whose chiral partners are, respectively, an axial-vector and a pseudovector [122, 123]. Patterns of chiral-symmetry restoration may be more complicated in this case. Nonetheless, all these theoretical calculations may be refined by experimental data resulting in a significantly deeper understanding of high-energy QCD.

## 5 Conclusions

There are many open questions in strong dynamics at present, out of which I have discussed two that appear to be relevant for NICA: glueballs and (axial-)vector mesons in vacuum and in medium.

Glueballs, although theoretically expected to emerge as bound states of gluons in the low-energy region of QCD, have remained elusive even after decades of research. One of the main reasons is a lack of precise experimental data. Glueball search would be aided greatly if SPD @ NICA were to measure  $2\pi$ ,  $2K$  and  $4\pi$  (and other) final states in the energy region where glueballs are expected to start emerging, *i.e.*, above  $\sim 1.5$  GeV.

These measurements regarding vacuum strong dynamics would have wider implications: since glueballs couple to  $\bar{q}q$  states already in vacuum they can be expected to influence  $\bar{q}q$  in-medium dynamics as well. Consequently, clearer data on glueballs in vacuum will permit a more precise prediction of dynamics at non-zero temperatures and densities – including chiral-symmetry restoration – where additional ambiguities are present, particularly regarding the behaviour of vector and axial-vector mesons such as mass shifts and in-medium broadening. Currently the possible in-medium modifications of glueballs are also unclear. Resolution of these questions can be aided by precise measurements at MPD and BM@N. Thus the entire NICA project appears to have a large potential to decisively increase our understanding of strong dynamics.

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